

# Electroweak Physics - Theoretical Overview

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## Physics of W and Z bosons

Introduction

Status of higher-order QCD and EW calculations

Work in progress: TeV4LHC Electroweak WG

Conclusions

## Standard Model Higgs physics

Introduction

Status of QCD predictions for Higgs production processes

EW one-loop corrections to  $H \rightarrow WW/ZZ \rightarrow 4f$

Conclusions

# Resources

- ▶ LEPEWWG website at  
<http://lepewwg.web.cern.ch/LEPEWWG> (status Winter 2006)
- ▶ CDF Physics Results website at  
<http://www-cdf.fnal.gov/physics/physics.html>
- ▶ D0 Physics Results website at  
<http://www-d0.fnal.gov/Run2Physics/WWW/results.htm>

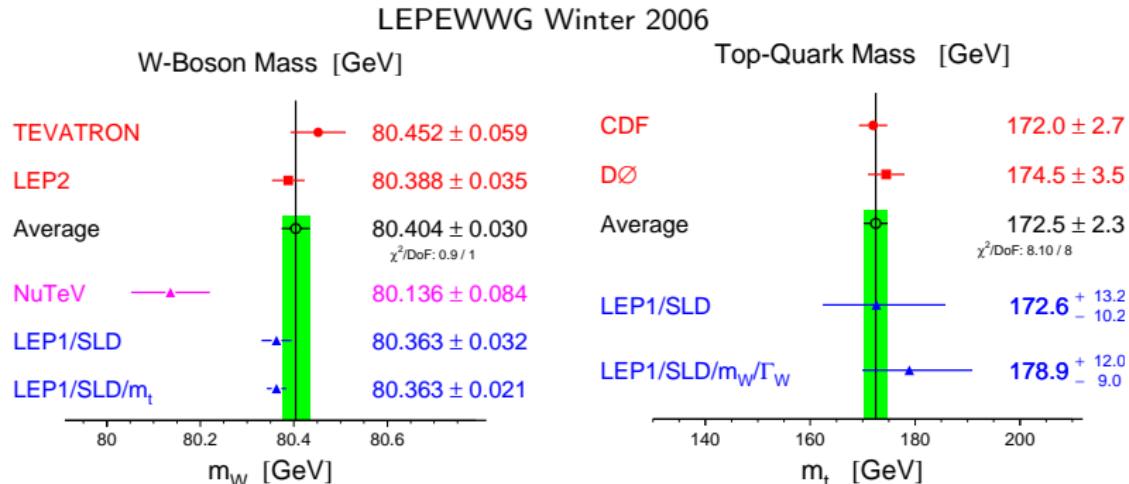
Many Thanks !

Please note: Experimental results have been chosen and are shown for illustration purposes only. For a detailed discussion please see the next 3 talks in this session.

# Physics of W and Z bosons

- ▶ W and Z production processes are one of the best, most precise probes of the Standard Model
- ▶ Precision measurement of the W mass and width (direct and indirect):  
 $d\sigma/dM_T$ ,  $d\sigma/dp_T(l)$  and ratio of  $\sigma_Z$  and  $\sigma_W$
- ▶ Detector calibration and luminosity monitoring:  
 $M_Z, \Gamma_Z$  from  $d\sigma/dM(l)$  at the Z peak and  $\sigma_{W,Z}$
- ▶ Constraints on quark PDFs:  
W charge asymmetry and Z rapidity distributions
- ▶ Search for new physics, e.g., heavy new gauge bosons (Z'):  
 $A_{FB}$  and  $d\sigma/dM(l)$  at high  $M(l)$

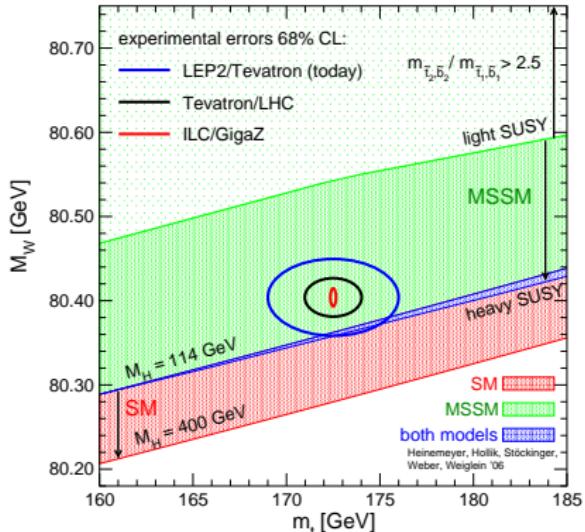
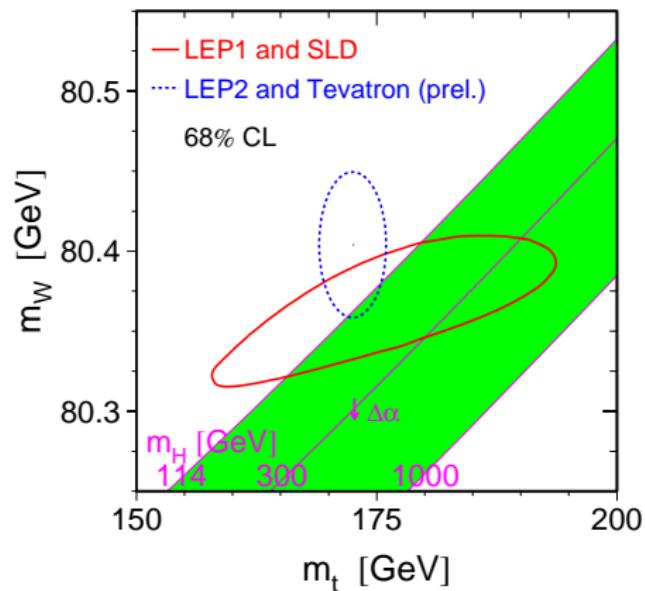
# The importance of a precise W mass measurement



uncertainty	now	Tevatron 2 $\text{fb}^{-1}$	LHC
$\delta M_W$ [MeV]	30	27	15
$\delta m_t$ [GeV]	2.3	2.7	1.0
$\delta M_H/M_H$ [%] (from all data)	47	35	18

from U.Baur *et al.*, hep-ph/0111314

# Constraint on $M_H$ and sensitivity to new physics

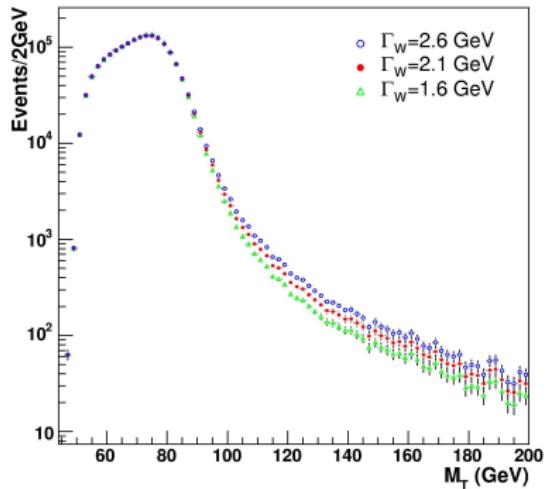
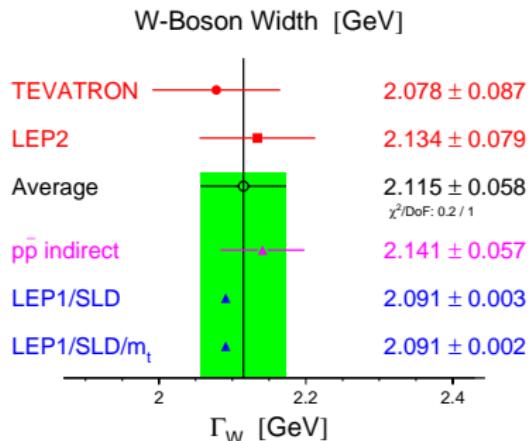


CERN-PH-EP/2005-051 (update: LEPEWWG webpage) S.Heinemeyer *et al.*, hep-ph/0604147

Constraint on SM Higgs mass:  $M_H = 89^{+42}_{-30}$  GeV at 68 % C.L.

# Direct and Indirect $\Gamma_W$ measurements

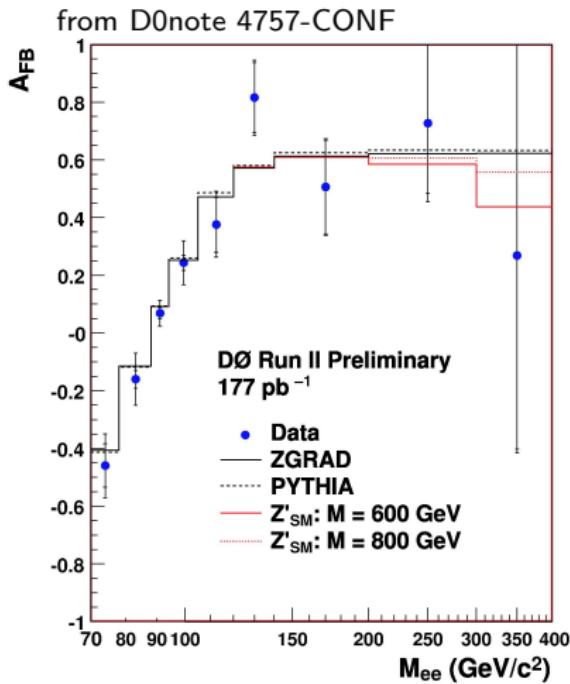
LEPEWWG Winter 2006



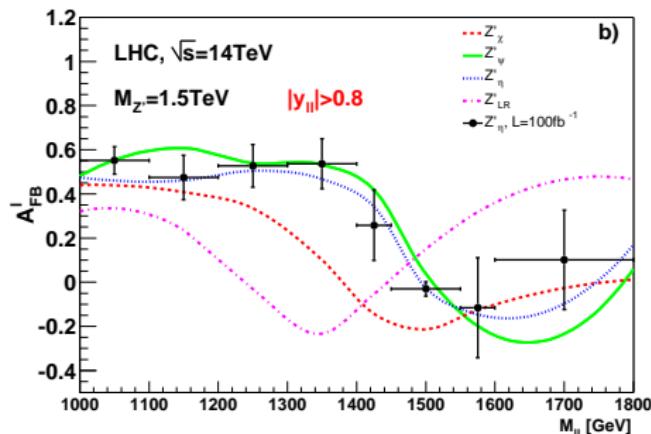
Direct measurement  
from D0note 4563-CONF (MC simulation)

Indirect measurement:  $R = \frac{\sigma_W}{\sigma_Z} \frac{\Gamma_Z}{\Gamma_{Z \rightarrow ll}} \frac{\Gamma_{W \rightarrow l\nu}}{\Gamma_W}$

# Search for new physics in $A_{FB}$ at high $M(l\bar{l})$ at the Tevatron and LHC

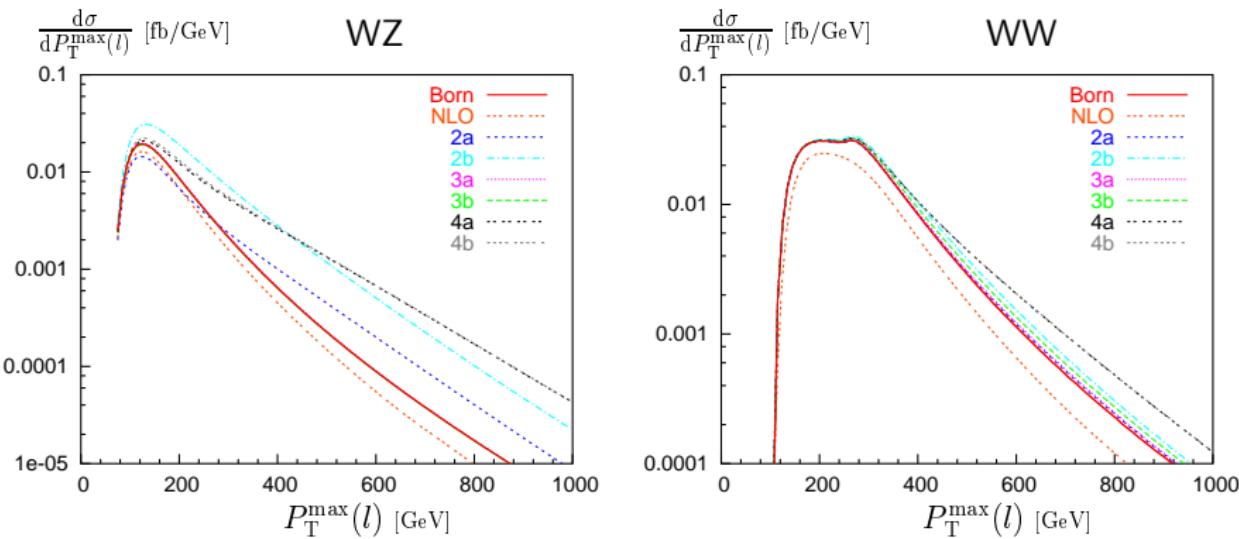


from M.Dittmar *et al*, PLB 583 (2004)  
**Forward backward asymmetry measurement**



# Anomalous Gauge Boson Couplings in WZ/WW production at the LHC

SM LO, NLO predictions vs. anomalous couplings scenarios:



from E.Accomando, A.Kaiser, hep-ph/0511088

EW corrections can fake signals of new physics !

# Status of higher-order QCD and EW calculations

## ► QCD radiative corrections to W/Z production:

exact up to  $\mathcal{O}(\alpha_s^2)$  (total cross sections) and soft gluon resummation ( $p_T(W, Z)$  distributions).

R.Hamberg *et al.*, NPB359 (1991); W.L.van Neerven *et al*, NBP382 (1992) ;  
W.T.Giele *et al*, NPB403 (1993); C.Balazs *et al*, PRD56 (1997) (RESBOS)

Fully differential distributions to W boson production and Z rapidity distribution up to  $\mathcal{O}(\alpha_s^2)$

K.Melnikov, F.Petriello, hep-ph/0603182; L.Dixon *et al.*, hep-ph/031226

## ► Electroweak (EW) corrections to Z and W boson production:

complete EW  $\mathcal{O}(\alpha)$  contribution and multiple final state photon radiation.

U.Baur *et al*, PRD65 (2002); C.M.Carloni Calame *et al*, JHEP05 (2005) and  
U.Baur, D.W., PRD70 (2004); S.Dittmaier, M.Krämer, PRD65 (2002);

A.Andonov *et al*, hep-ph/0506110, L.Akhushevich *et al*(2003);

W.Placzek *et al*, EPJC29 (2003); C.M.Carloni Calame *et al*, PRD69 (2004)

Hadron Collider Physics  
Symposium 2006

# Tools for W/Z production at the Tevatron and LHC

Most of these calculations have been implemented in MC programs: (see also talk by S.Jadach at CERN MC4LHC workshop)

HORACE: Multiple photon radiation from final state in W/Z production as solution of QED DGLAP evolution for lepton SF. C.M.Carloni Calame *et al*, PRD69 (2004)

RESBOS: QCD corrections to W/Z production, soft gluon resummation.  
C.Balazs, C.P.Yuan, PRD56 (1997)

<http://www.pa.msu.edu/~balazs/ResBos/>

WGRAD2: QED  $\mathcal{O}(\alpha)$  and weak corrections to W production. U.Baur, D.W., PRD70 (2004)

<http://ubpheno.physics.buffalo.edu/~dow/wgrad.tar.gz>

WINHAC: Multiple photon radiation from final state in W production, YFS exponentiation of soft photons. W.Placzek, S.Jadach, EPJC20 (2003)

<http://placzek.home.cern.ch/placzek/winhac>

ZGRAD2: QED  $\mathcal{O}(\alpha)$  and weak corrections to Z boson production with proper treatment of higher-order terms around the Z resonance. U.Baur *et al* PRD65 (2002)

<http://ubhex.physics.buffalo.edu/~baur/zgrad2.tar.gz>

and also DYRAD, MCFM, MC@NLO, PHOTOS, SANC (semi-analytical),...

**Next step:** Use the available tools for precision studies of W/Z observables to answer the following questions:

- ▶ What is the impact of higher-order corrections and how does it compare to the anticipated experimental precision ?
- ▶ What is the residual theoretical uncertainty of the best predictions ?
- ▶ Do we need improvements to be able to fully exploit the physics potential at the Tevatron and the LHC ?

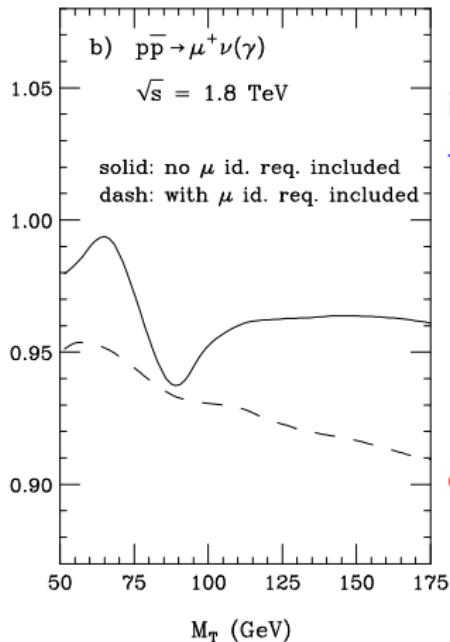
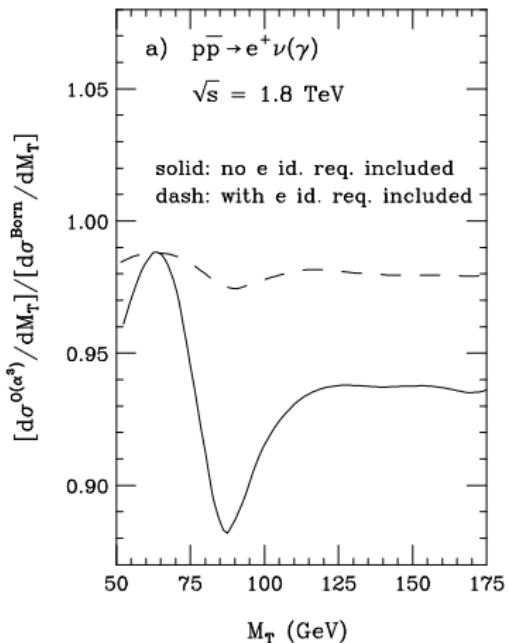
**Goal: Experimental precision not to be limited by theory uncertainty !**

# Characteristics of EW corrections

- ▶ **Final-state photon radiation (FSR):**  
in sufficiently inclusive observables the mass singularities completely cancel (KLN theorem). But, depending on the experimental set up, large contributions of the form  $\alpha \log(s/m_I^2)$  can survive.
- ▶ **Initial-state photon radiation (ISR):**  
mass singularities always survive but are absorbed by universal collinear counterterms to the parton distribution functions (mass factorization done in complete analogy to QCD).
  - ▶ introduces dependence on QED factorization scheme (in analogy to QCD, a  $\overline{DIS}$  and  $\overline{MS}$  scheme has been introduced)
  - ▶ PDFs including QED corrections have been made available by the MRST collaboration A.D.Roberts *et al.*, EPJC39 (2005).
- ▶ **Electroweak corrections at large energies,  $s \gg M_{W,Z}^2$ :**  
Sudakov-like contributions of the form  $\alpha \log^2(s/M_{Z,W}^2)$  can significantly enhance one-loop corrections.

# Impact of EW corrections on $M_T(l\nu)$ at the Tevatron

$$M_T = \sqrt{2p_T(l)p_T(\nu)(1 - \cos\Phi^{l\nu})}$$



inclusive vs. exclusive  
treatment of photon

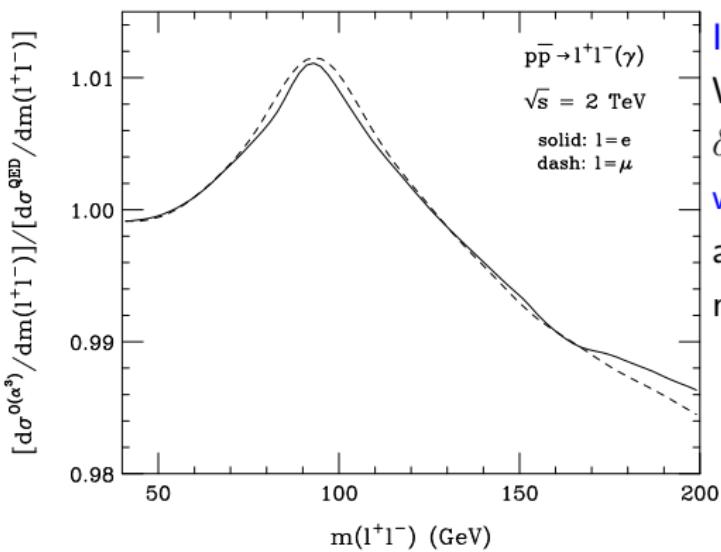
effect of  $\log(s/m_\mu^2)$

from U.Baur *et al*, PRD59 (1999)

# Impact of electroweak corrections on the W mass

$M_W$ extracted from $M_T(l\nu)$ at RUN I: $\delta M_W^{exp} = 59$ MeV	
final state QED (approximation) F.A.Berends <i>et al</i> , Z.Phys.C27 (1985)	Shift due to FSR (RUN I): $-65 \pm 20$ ( $-168 \pm 20$ ) MeV in the electron (muon) case. $\delta M_W^{theory} = 10 - 20$ MeV
$M_W$ extracted from $M_T(l\nu)$ at RUN II: $\delta M_W^{exp} = 27$ MeV	
full $\mathcal{O}(\alpha)$ contribution to resonant W production in a pole approx. W.Hollik, D.W., PRD55 (1997)	shift in $M_W$ : $\delta M_W = 10$ MeV
full $\mathcal{O}(\alpha)$ electroweak corrections U.Baur, D.W., PRD70 (2004)	high $Q^2$ , $\Gamma_W$
real two-photon radiation in W, Z production U.Baur <i>et al</i> , PRD61 (2000)	significantly changes shape of $M_T$
multiple final state photon radiation C.M.Carloni Calame <i>et al</i> , PRD69 (2004)	$\delta M_W = 2(10)$ MeV in the $e(\mu)$ case

# Impact of weak corrections on $M(\|)$ at the Tevatron - at the Z resonance



Impact on extraction of  $M_Z$ :

With approximation by Berends,Kleiss:

$\delta M_Z = -100 \text{ (-300) MeV (}e(\mu)\text{ case)}$

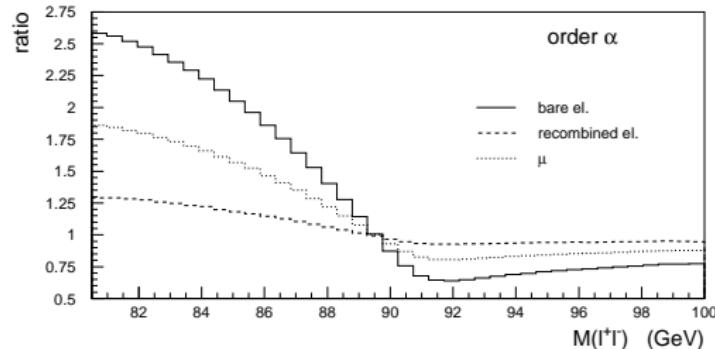
with full  $\mathcal{O}(\alpha)$ :

additional shift of  $-10 \text{ MeV}$

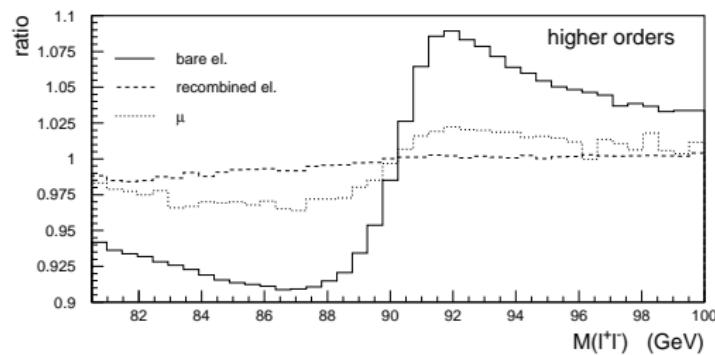
mainly due to FSR

from U.Baur *et al*, PRD65 (2002)

# Impact of multiple photon radiation on $M(II)$ at the Tevatron

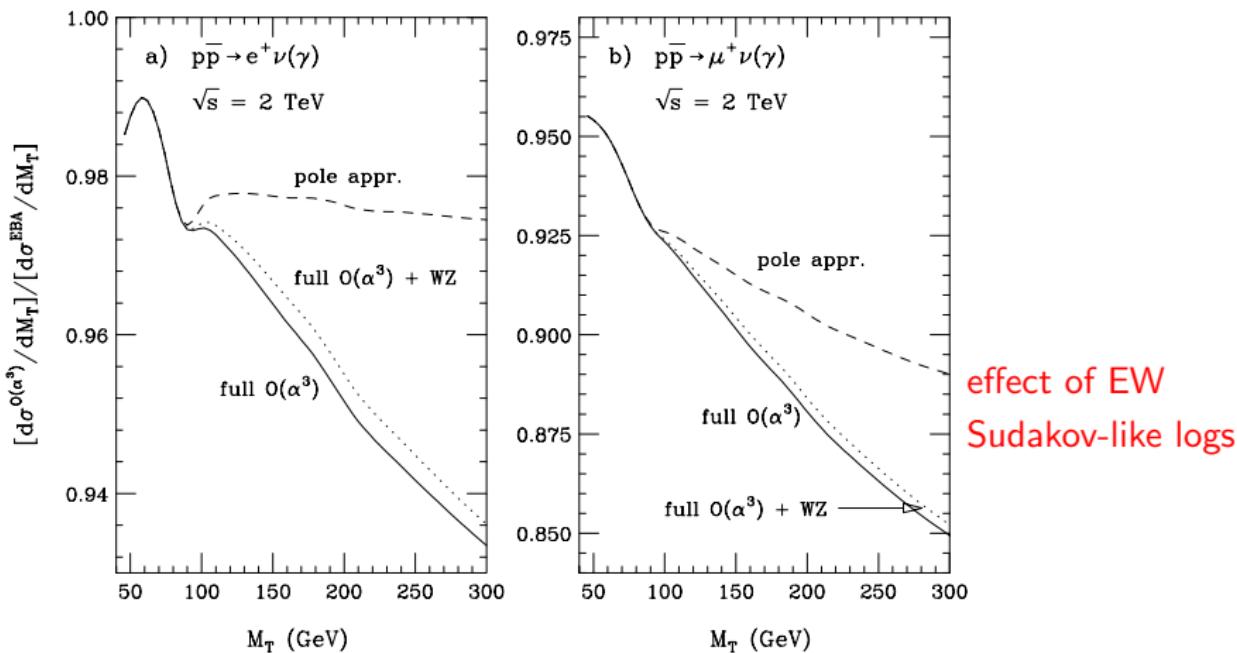


Effect on  $M_Z$ :  
10% of NLO shift.



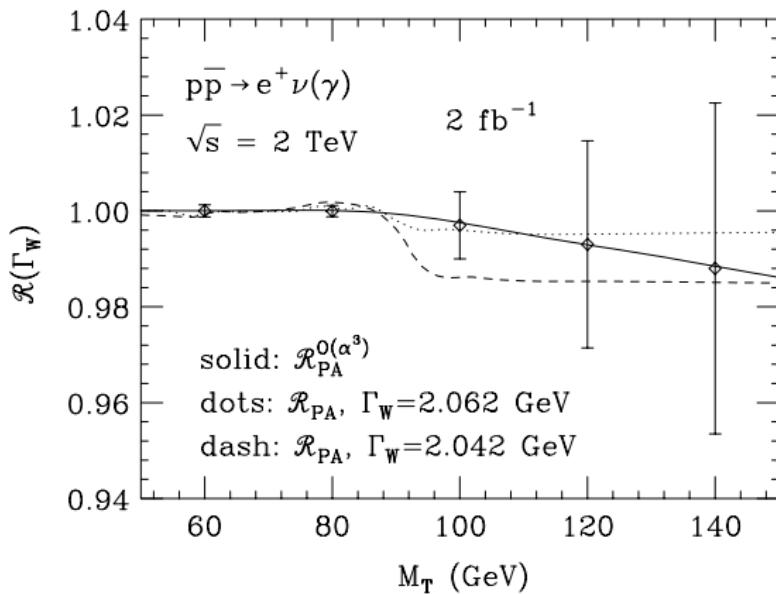
from C.M. Carloni Calame *et al.*, hep-ph/0502218 (HORACE)

# Pole approximation vs. complete EW calculation at the Tevatron - above the W peak



from U.Baur, D.W., PRD70 (2004)

# Impact of non-resonant EW corrections on $\Gamma_W$ at the Tevatron



$$\frac{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W^{SM}}}{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W}} \propto \frac{\Gamma_W}{\Gamma_W^{SM}}$$

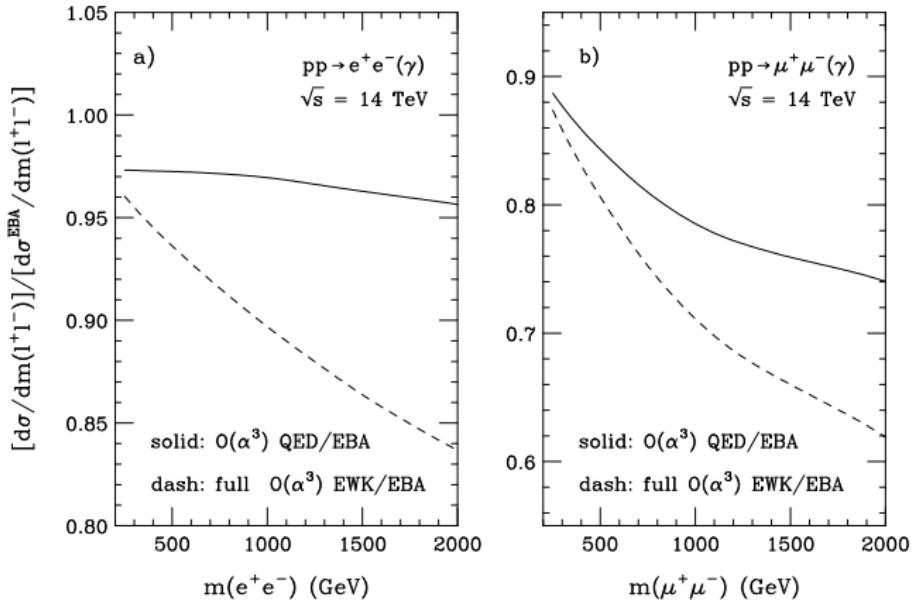
input:  $\Gamma_W^{SM} = 2.072 \text{ GeV}$

size of non-res. corr. is of same order as effects due to non-SM values of  $\Gamma_W$

$\chi^2$  fit: ignoring these corrections shifts  $\Gamma_W$  by -7.2 MeV ( $\delta\Gamma_W^{exp} = 87 \text{ MeV}$ )

from U.Baur, D.W., PRD70 (2004)

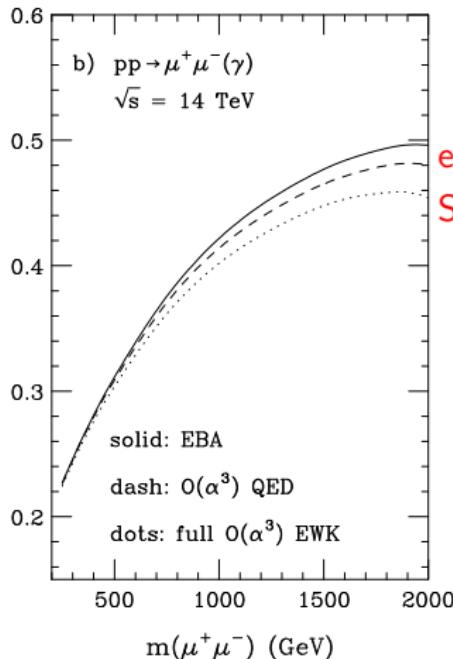
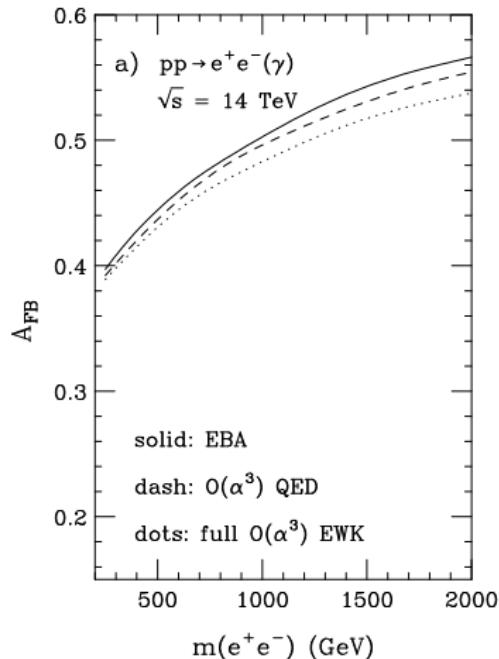
# Impact of EW corrections on $M(II)$ at the LHC - above the Z peak



effect of EW  
Sudakov-like logs

from U.Baur *et al*, PRD65 (2002)

# Impact of EW corrections on $A_{FB}$ at the LHC



from U.Baur *et al*, PRD65 (2002)

# Enhanced EW corrections at high energies

- ▶ At energies  $\sqrt{s} \gg M_{W,Z}$  EW corrections are enhanced by

$$\alpha^L \log^N\left(\frac{s}{M_V^2}\right) ; \quad 1 \leq N \leq 2L \quad (L = 1(1-loop), \dots)$$

Origin: Remnants of UV singularities after renormalization + soft/collinear ISR and FSR emission of virtual and real W/Z bosons.  
In contrast to QED,QCD, Bloch-Nordsiek theorem is violated, i.e. also in inclusive observable these corrections do not completely cancel.

W/Z mass is physical cut-off: real W/Z is usually not included since it leads to a different initial/final state.

- ▶ EW logarithmic corrections to 4-fermion processes are known up to 2-loop  $N^3 LL$  order and are available in form of compact analytical formula.

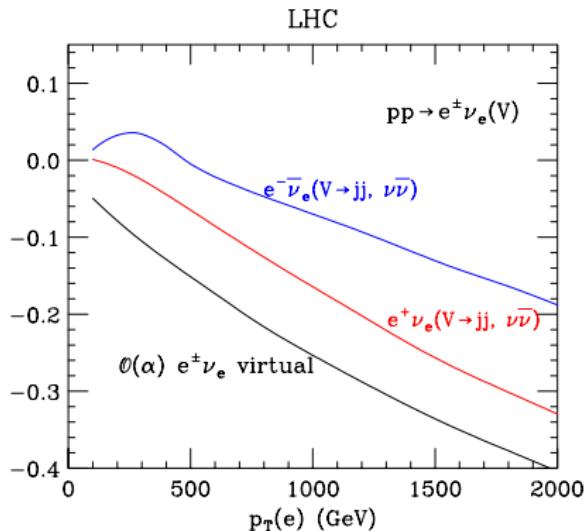
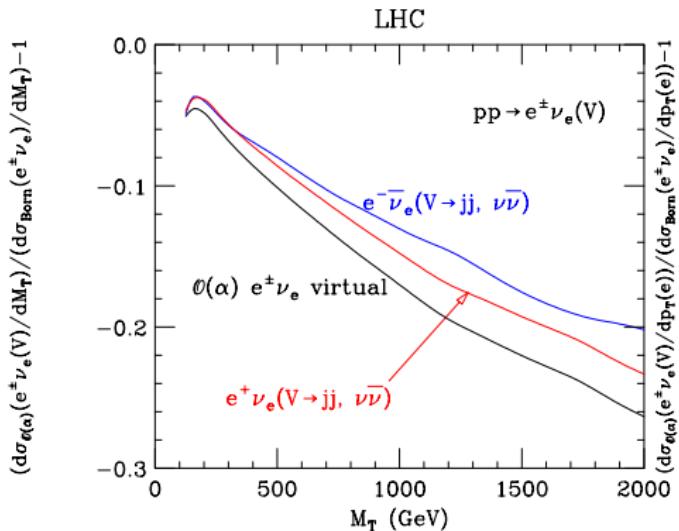
First studies of distributions at the LHC show that these higher order corrections are numerically important at high energies.

For a review see, e.g., J.Kühn's talk at Radcor 2005:

<http://www-conf.kek.jp/radcor05>

# How numerically important are EW Sudakov logarithms ?

Depends on the observable, i.e. the more inclusive the observable in the treatment of the weak gauge boson, the less numerical important are these EW contributions:

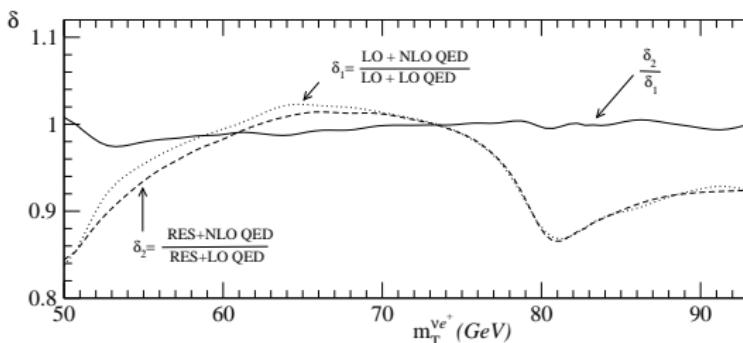
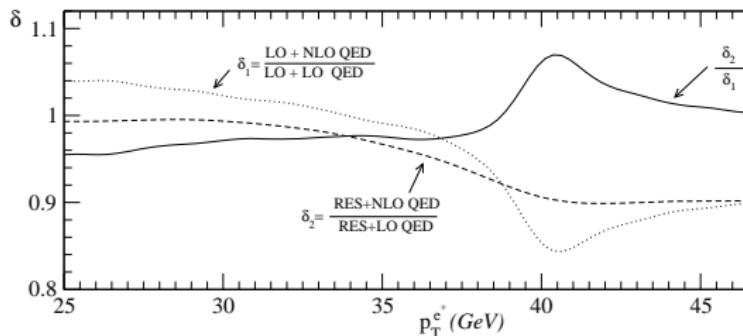


Talk given by U.Baur at Pheno 2006:

<http://www.pheno.info/symposia/pheno06>

# Impact of combined EW and QCD corrections using ResBos

From C.-P.Yuan, Q.-H.Cao, PRL93 (2004)



ResBos combines QCD ISR  
and QED FSR.

Effects of QED when combined  
with QCD differ from  
the only QED case !

# Work in progress: TeVLHC Electroweak WG

see <http://conferences.fnal.gov/tev4lhc>

- ▶ Tuned comparison of available Monte Carlo programs that provide precise predictions for  $W/Z$  observables a la LEPI/II CERN yellow books (RESBOS, W/ZGRAD, HORACE, WINHAC, SANC, PHOTOS,...): first studies in LesHouches proceedings, hep-ph/0406152
  - ▶ Provide an estimate of remaining theoretical uncertainties due to missing higher order corrections, PDF uncertainties, ....
  - ▶ Identify necessary improvements to match experimental precision.
  - ▶ Provide a recommendation of how to implement (dominant) electroweak corrections in multi-purpose event generators.

## Recent Improvements:

**QCD** New in ResBos:

- ▶ Improved fit for nonperturbative part to  $q_T$  distribution (*Konychev, Nadolsky*)
- ▶ Final state QED contribution included (*Cao, Yuan*)

Fully differential W distributions known at NNLO QCD (*Melnikov, Petriello*).

**EW** Multiple photon radiation in W and Z production implemented in MC program HORACE (*Carloni Calame, Montagna, Nicrosini, Treccani*) and WINHAC (*Jadach, Placzek*).

QED corrections included in extraction of PDFs (*MRST collaboration*)

# Conclusions

- ▶ W and Z boson physics at hadron colliders offers plentiful and unique opportunities to test the SM and search for signals of physics beyond the SM.
- ▶ Impressive progress has been made in providing precise predictions at NLO, NNLO and higher (leading logarithms).
- ▶ We are now in the process to determine if the tools provided are sufficient in view of the anticipated experimental capabilities for EW precision physics at the Tevatron and the LHC.

This involves a careful study of the residual theoretical uncertainties (TeV4LHC workshop).

# Conclusions: Work in Progress

Ongoing work by the authors of  
WINHAC, RESBOS, HORACE, WGRAD/ZGRAD:

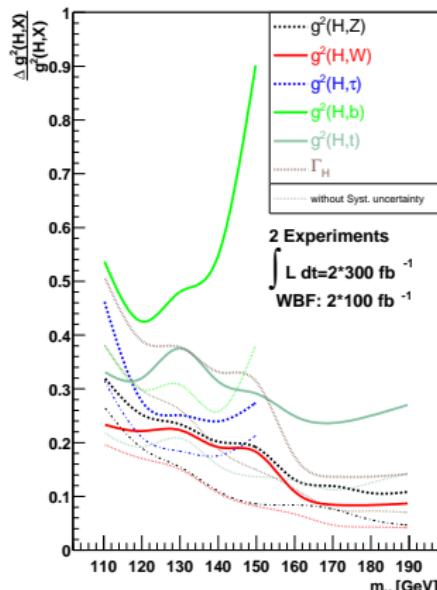
- ▶ Combination of EW and QCD corrections in one MC generator
- ▶ Interface of higher-order EW calculations, i.e. multiple photon radiation from final state leptons and EW Sudakov logarithms, with fixed  $\mathcal{O}(\alpha)$  calculations.

Moreover:

Inclusion of mixed QED/QCD  $\mathcal{O}(\alpha\alpha_s)$  corrections.

# Standard Model Higgs physics

Once a Higgs boson is discovered, to fully exploit the potential of the LHC to determine its properties it is crucial to provide higher-order QCD and EW calculations of signal and background processes.



Example:

Extraction of SM Higgs couplings at the LHC:

LHC can measure Higgs couplings to  $t, \tau, W, Z$  with 10-20 % accuracy in multi-Higgs-doublet models ( $300 \text{ fb}^{-1}$ )

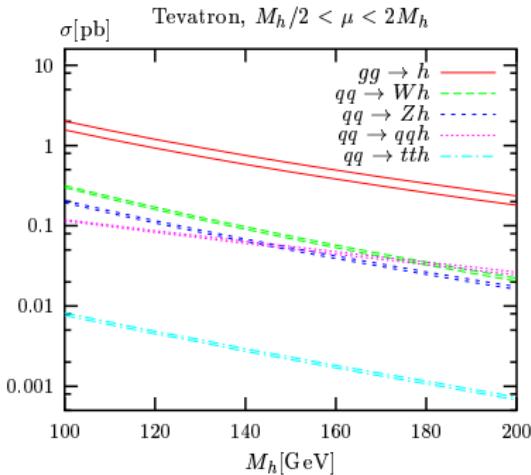
from M.Dührssen *et al.*, hep-ph/0407190  
 for an update see F.Petriello's talks

# State-of-the-art of QCD predictions for Higgs production at hadron colliders:

Dominant production modes:  $gg \rightarrow H$  (background very large);  
 $q\bar{q} \rightarrow WH, ZH$  (most promising for leptonic decay of W/Z)

production process	$\sigma_{\text{NLO,NNLO}}$ by
$gg \rightarrow H$	S.Dawson, NPB 359 (1991); A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser, C.R.Schmidt, JHEP (2002); V.Ravindran <i>et al.</i> , NPB 634 (2002); D.de Florian <i>et al.</i> , PRL 82 (1999) (distrib.) V.Ravindran <i>et al.</i> , NPB 665 (2003) (NNLO) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNLO)
$q\bar{q} \rightarrow (W, Z)H$	T.Han, S.Willenbrock, PLB 273 (1991)
$q\bar{q} \rightarrow q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992) T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003) (distrib.)
$gg, q\bar{q} \rightarrow t\bar{t}H$	W.Beenakker <i>et al.</i> , PRL 87 (2001), NPB 653 (2003) S.Dawson <i>et al.</i> , PRL 87 (2001), PRD 65 (2002), PRD 68 (2003)
$gg, q\bar{q} \rightarrow b\bar{b}H$	S.Dittmaier, M.Krämer, M.Spira, PRD 70 (2004) S.Dawson <i>et al.</i> , PRD 69 (2004)
$gb(b) \rightarrow b(b)H$	for a review see, e.g., S.Dawson <i>et al.</i> , MPLA 21 (2006)
$b\bar{b} \rightarrow H$	for a review see, e.g., S.Dawson <i>et al.</i> , MPLA 21 (2006); R.Harlander, W.Kilgore, PRD 68 (2003) (NNLO)

$\sigma_{NLO,NNLO}$  for Higgs production processes at hadron colliders:

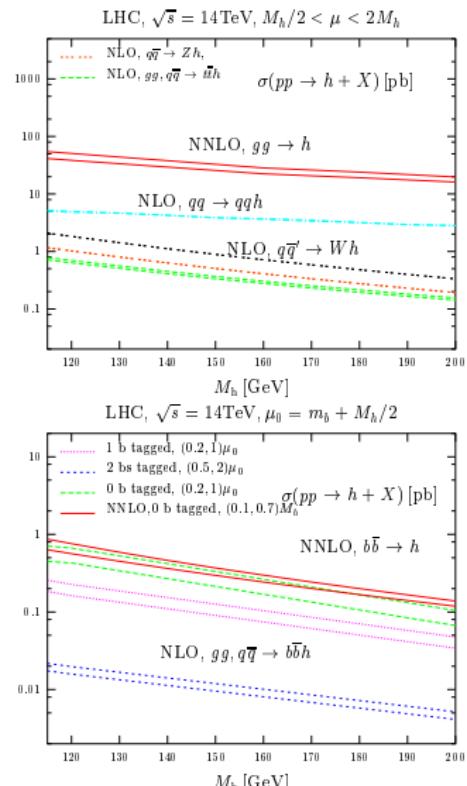


from S.Dawson *et al.*, hep-ph/0210109

**tth7:**  $\mu$  varied between  $\mu_0 = m_t + M_h/2$  and  $2\mu_0$ .

from S.Dawson *et al.*, in prep. (prelim.)

Many thanks to W.Kilgore and R.Harlander for providing their NNLO results.

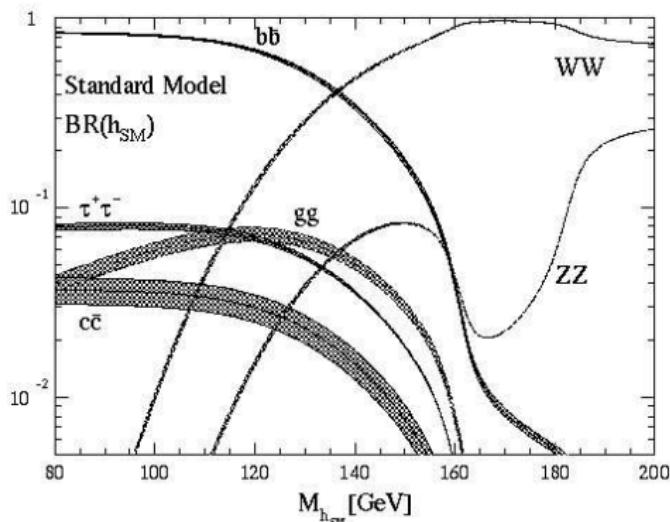


Dominant decay modes:

$M_H < 135$  GeV:  $H \rightarrow b\bar{b}$  with  $BR = 43\%$ ,

$M_H > 135$  GeV:  $H \rightarrow W^+W^-$  with  $BR = 40\%$

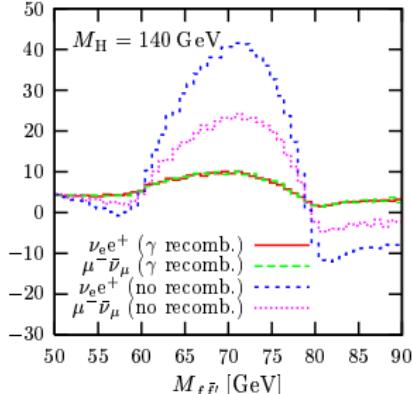
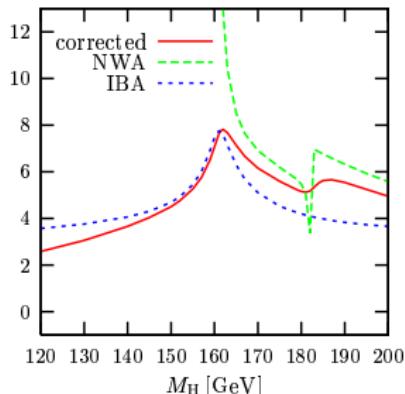
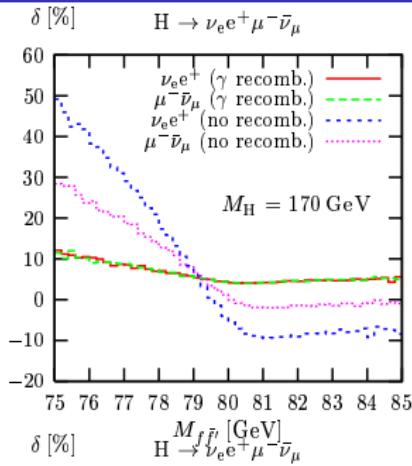
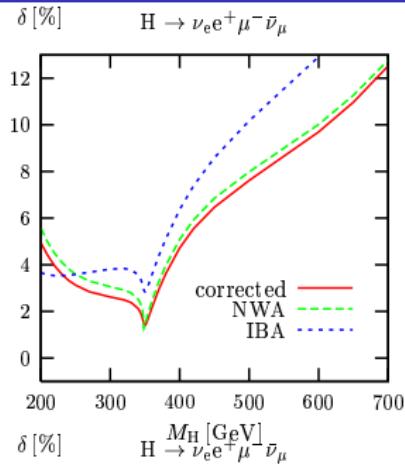
Branching ratios of the dominant SM Higgs decay modes  
(including QCD corrections):



from M.Carena and H.Haber,  
[hep-ph/0208209](#)  
HDECAY (A.Djouadi *et al.*)  
M.Spira, [hep-ph/9810289](#)

# EW one-loop corrections to $H \rightarrow WW \rightarrow 4f$

NWA ok above  
WW threshold



Size of EW corr.:  
about 5-10 %

from A.Bredenstein et al., hep-ph/0604011

# Conclusions

- ▶ Predictions for SM Higgs production and decay processes are under good theoretical control.  
Possible improvements: Interface of resummed QCD calculations with fixed order calculations (e.g., threshold logarithms in Higgs production in association with heavy quarks).
- ▶ Predictions for background processes also need to include higher order QCD corrections.